***DAMAGE TOLERANCE OF COMPOSITE SANDWICH AIRFRAME STRUCTURES***

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**<u>Program Overview</u>**

Sandwich constructions are widely used in airframe structural applications due to the distinct advantages they offer over other metallic and/or composite (monolithic laminate) structural configurations in terms of stiffness, stability, specific strength, corrosion resistance, and above all the weight savings. However, the sandwich structures are very susceptible to localized transverse loads, due to their inherent construction. The skin core combination is not very resilient when subjected to localized normal loads (normal to surface of the panels). These rogue loads are prevalent during normal operational procedures, which include service and maintenance, service equipment, baggage handling, etc. Also, damage may be inflicted by operational loads arising due to runway debris impact and hail impact. The understanding of the damage characteristics due to such events and the corresponding stiffness reductions is detrimental to the long-term structural integrity of the airframe.

In an effort to bridge the gap between the ever-growing composite sandwich application for airframes and the lack of sufficient knowledgebase for damage tolerant design(s) and certification, an experimental investigation was initiated at the Wichita State University. A thorough review of the existing literature on damage resistance and tolerance of sandwich structures revealed several unresolved and under explored issues[1]. Most damage tolerance programs had considered impact damage due to impactor diameters less than 1.5″ in diameter and the damage states typically consisted of visible skin fractures with appreciable residual indentation. The residual indentation depth was popularly used as a damage metric for defining Barely Visible Impact Damage (BVID) even though it was purely based on damage visibility. Several nondestructive test methods and field inspection techniques have also been used to detect and quantify the damage magnitude without any reference to the damage morphology and more importantly the residual properties of the sandwich structure. In this investigation efforts were made to address the effects of impactor diameter on the damage resistance and tolerance, detectability of impact damage using filed inspection techniques, effects of curvatures and fatigue loading. The key observations associated with the different subtasks are summarized in the following paragraphs.

Based on the extensive literature survey [1], candidate material systems and sandwich configurations were chosen for this study [2]. The sandwich skins and core types were representative of the current practices in the GA industry. Plain weave carbon fabric preimpregnated in epoxy resin (NEWPORT NB321/3K70P) was used for the skins and Nomex honeycomb cores (PLASCORE PN2-3/16-3.0) were used as the sandwich core. Three different quasi-isotropic layup schedules for the facesheets and two thicknesses for the core were used. The skin layup schedules are similar to those used in some of the GA aircraft. The core thicknesses used were 3/8″ and 3/4″. Therefore, a total of six sandwich configurations were used for this study. The sandwich layup schedules used were $[(90/45)_n/CORE/(45/90)_n]$, n=1,2 and 3.

The impact damage resistance and damage tolerance characteristics of honeycomb core sandwich specimens were studied experimentally. The impact tests were conducted at a nominal constant impact velocity of 96.6 in/sec, at various energy levels. Hemispherical steel impactors with diameters of 1.00″ and 3.00″ were used for this preliminary study. The impact test results indicated that the larger diameter impactor produced higher impact forces when compared to that of the smaller impactor. This trend was amplified at higher energy levels and tends to be negligible as the impact energy levels decrease. This was attributed to the contrasting contact load distributions associated with the size of the impactors.

The impacted specimens were subsequently inspected for damage using non-destructive inspection (NDI) methods. Damage metrics such as planar damage area (using Through Transmission Ultrasonic C-Scan) and residual indentation depths were used to implicitly quantify the damage state. The results indicated that larger diameter impactor produces a very benign appearing damage state, wherein, no surface fracture/ cracks nor visually perceptible levels of indentation exists, but the NDI did indicate a very large damaged region (see figure 1). A select number of impact experiments were repeated, the energy levels chosen from the current experience, and the specimens were subjected to destructive sectioning to study the true nature of the damage. It was observed that for specimens impacted with larger diameter impactor, the sandwich core had undergone localized crushing close to the impacted skin over a considerable area. However, the impacted skin which had not suffered any noticeable damage, thus retaining most of its original stiffness (and aided by the now more compliant damaged core), had sprung back close to its original state. This damage scenario proved to be the most elusive when the impacted specimens were inspected using a typical visual inspection protocol. It was conclusively shown that the visual inspection methods are very misleading and the residual indentation cannot be used as a BVID metric for damage tolerance programs.

The effects of various damage states on the performance of the sandwich panels under load was quantified using an uni-axial edgewise compression test, popularly known as ëCompression After Impactí (CAI) test. The CAI test results revealed that the damage states due to the larger diameter impactor behaved as geometric imperfections leading to a local stability governed failure mode. Further, the failure loads corresponding to the buckling mode were well below that corresponding to a pure compressive failure of the skins associated with damage states due to smaller diameter impactor, which were more effective as stress raisers (figure 1).

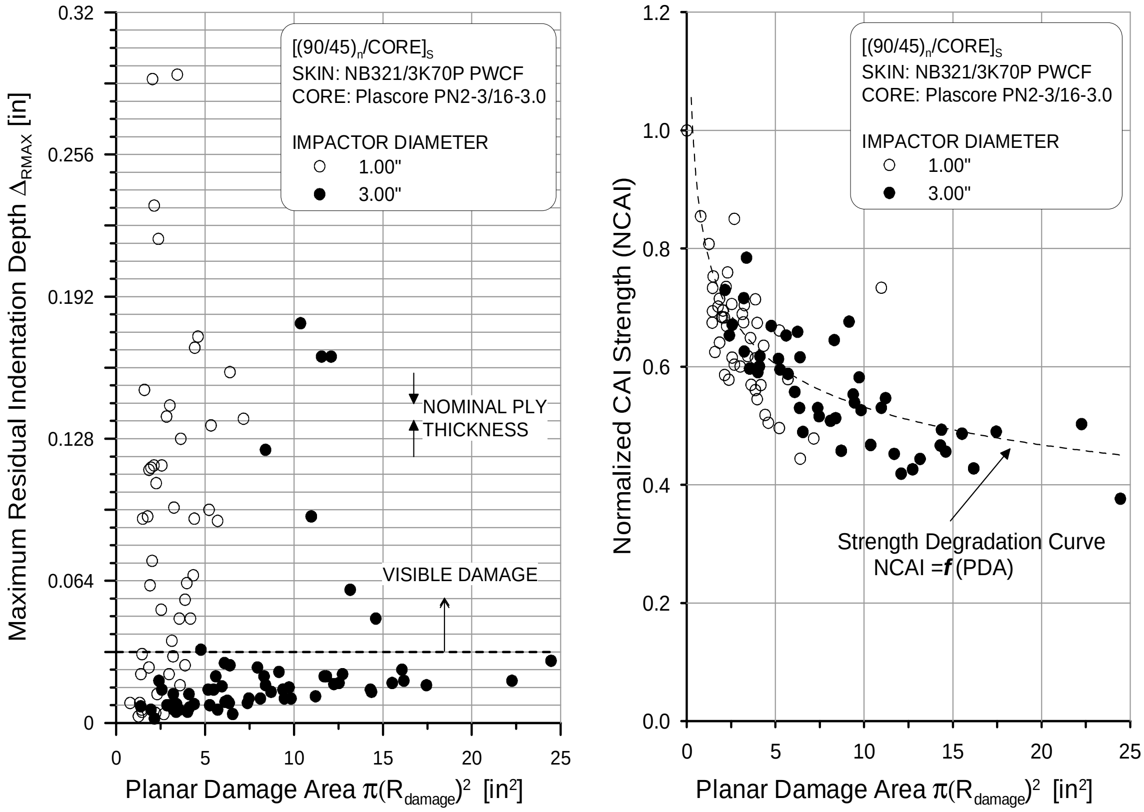


Figure (1): Combinations of planar damage area and maximum residual indentation depths for sandwich specimens impacted with 1″ and 3″ impactors, and residual compressive strengths as a function of planar damage areas.

From the aforementioned observations, it became necessary that the field inspection techniques must detect the planar damage size effectively to implement the damage tolerance programs. Thus, several candidate detection techniques/systems were evaluated in collaboration with the Sandia National Labatories. The field inspection methods used were manual impact tap hammer (Airbus model), the instrumented tap tester (Mitsui Woodpecker) , and the mechanical impedance analysis (V-95 Bondcheck). These methods were used to detect damage in both honeycomb and foam core sandwich panels impacted at different energy levels. The planar damage radius delineated by the field inspection techniques were compared with that of the TTU C-scan. The facesheet thickness was found to be the variable that influenced the performance of field inspection techniques (see figure 2), in determining the subsurface core damage that was of particular interest.

Based on the limited experimental results, it was concluded that the detection of impact damage in honeycomb and foam core sandwich panels cannot be accomplished to the same level of accuracy using a single Field Inspection Technique. The experimental data suggested that the impact damage in honeycomb core sandwich panels can be better detected by a technique that measures the local stiffness of the sandwich, while the damage in foam core panels can be better assessed with a technique relying on the measurement of acoustic impedance.

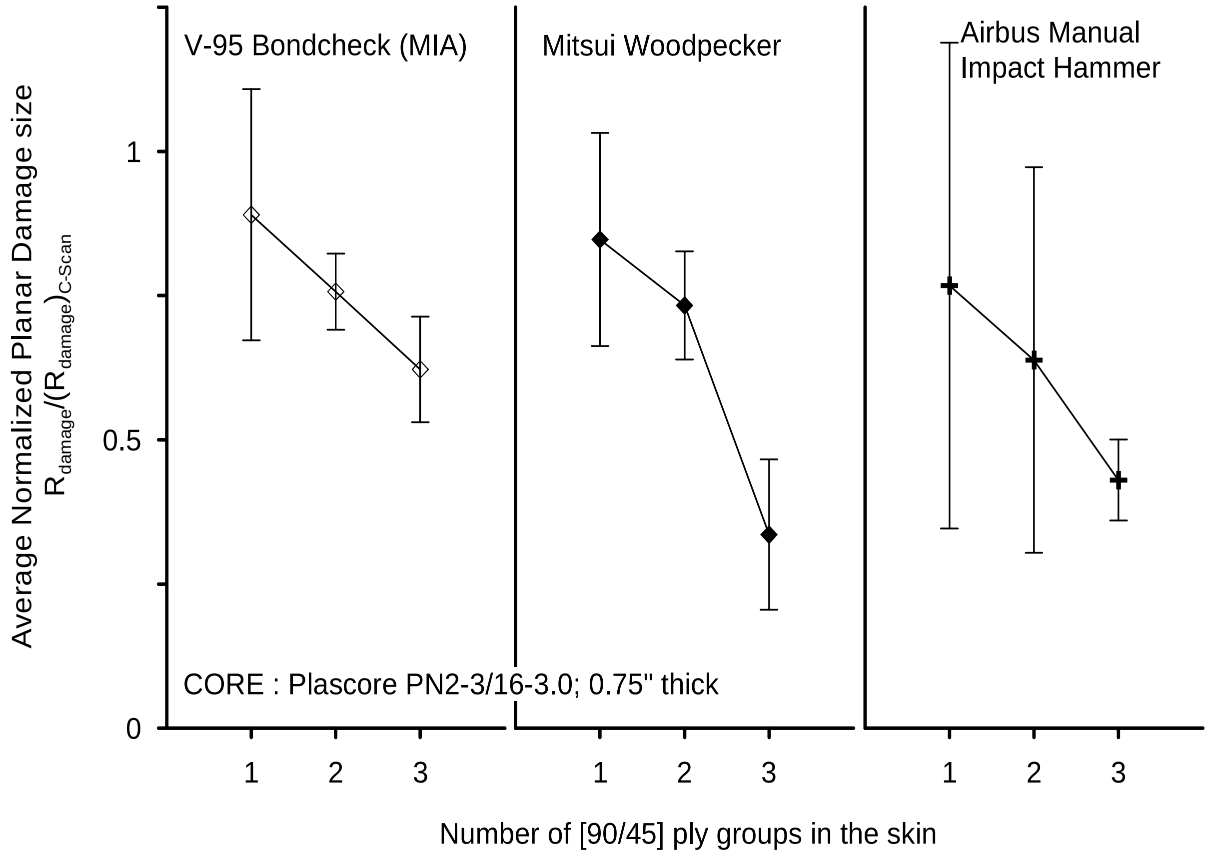


Figure 2: Normalized damage size for honeycomb core sandwich panels with different skin thicknesses.

The damage resistance and tolerance investigations for sandwich panels have been mostly limited to flat panels. However, the airframe structures are not necessarily flat and certain curvatures are associated with their geometry as dictated by the aerodynamic design. It would thus be important to understand the effects of panel curvature on the impact response and associated impact damage metrics in sandwich panels. In this study, a limited experimental investigation was conducted to observe the effects of curvature on the damage resistance of cylindrical sandwich panels. Three internal radii (see figure 3) of curvature of $R_{INT1}$=6.00″, $R_{INT2}$=24.00″ and $R_{INT3}$=48.00″ were used for the specimens in the present study. The above radii are representative of different locations on a general aviation airframe. The cylindrical sandwich specimens were impacted on the convex side at their respective geometric centers. The specimens were supported along their longitudinal edges using three different boundary supports with varying degrees of end fixity [ref].

The facesheets of the curved sandwich panels were made of NB321/3K70P Plain Weave Carbon prepreg. The core material used was Plascore PN2-3/16-x.x which had a thickness of 0.375″. The core density used for majority of the sandwich panels was 3.0 lb/ft$^3$, while a limited number of specimens were made with core densities of 4.5 lb/ft$^3$ and 6.0 lb/ft$^3$. The facesheets were bonded to the core using Hysol 9628.060 PSF NW film adhesive, in a co-cure, co-bond process. The sandwich layup configurations investigated were $[(90/45)/CORE]_S$ and $[(90/45)_2/CORE]_S$.

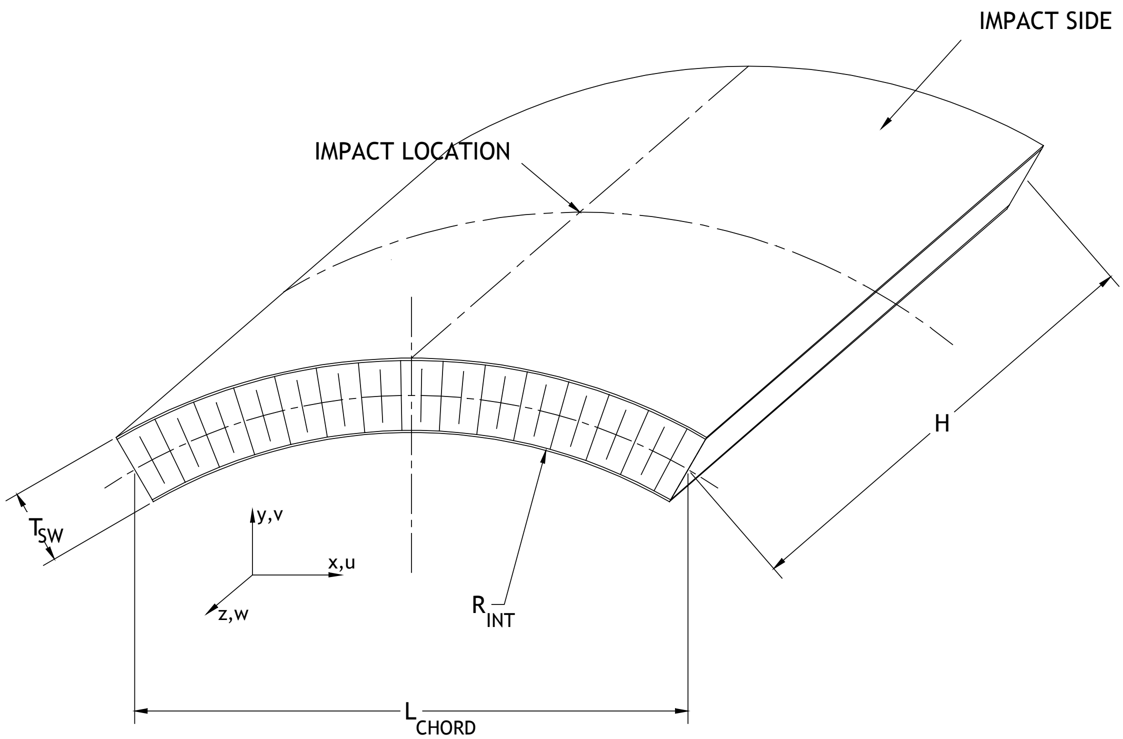


Figure 3: Geometry of curved panels used in the investigation.

The curved panels were impacted with 1″ and 3″ diameter impactors at different energy levels. The impacted panels were then inspected for damage and the effects of specimen radius on the planar damage area and the residual indentation depth were observed. The planar damage area was observed to increase with decreasing $R_{INT}$. In contrast to the planar damage area, the maximum residual indentation depths increased with increase in internal radius $R_{INT}$. The low residual indentations in curved sandwich panels can be attributed to the high restoring force associated with the curved facesheets. The facesheets collapse on the core during the loading phase creates damage in the core. During unloading, the facesheet tends to pull itself back to its undeformed position, while the core tends to pull it down creating the residual indentation. In curved panels, the moments generated in the skin are higher compared to the flat panels; thus, relatively low indentations will be observed. Therefore, the visual inspections for sandwich structures impacted with larger diameter (blunt) impactors will be more difficult. For smaller impactors, the impact damage will be more conspicuous because of the presence of skin fractures.

The behavior of impact-damaged sandwich panels under the action of fatigue loads was investigated experimentally. The impact damage states due to the 3.00″ diameter impactor was of particular interest because of the high degradation of residual strengths associated with such damage states and also the difficulties in detecting them using nondestructive inspection. The fatigue lives associated with different levels of impact damage in both honeycomb core and foam core sandwich panels were studied. The primary objectives of this exercise are:

1. To study the fatigue life of sandwich specimens with two levels of impact damage at different stress levels.

2. Observe the growth of damage if any, e.g., $2R_{damage}$

3. Monitor further degradation of residual strength due to a pre-specified infinite life $N_{\infty}$.

The behavior of impact damage in both honeycomb and foam core sandwich panels were investigated. The honeycomb core sandwich panels were used with NB321/3K70 Plain Weave Carbon facesheets while the foam core sandwich panels used NB321/7781 Satin Weave fiberglass facesheets. The sandwich configurations used in the current study are summarized in table 1.

TABLE 1. MATERIAL SYSTEMS AND SANDWICH CONFIGURATIONS USED IN THE FATIGUE PROGRAM

| **Sandwich Type** | Honeycomb Core Panels | Foam Core Panels |
|---|---|---|
| **Facesheet Material** | NB321/3K70 Plain Weave Carbon prepreg. | NB321/7781 Satin Weave Fiberglass prepreg. |
| **Layup Schedules** | $[(90/45)/CORE]_S$, $[(90/45)_2/CORE]_S$ | |
| **Core Material** | Plascore PN2-3/16-4.5; 0.75″ thick | DivinyCell HT-70; 0.75″ thick |
| **Adhesive** | Hysol 9628.060 PSF NW film adhesive | |

The following specifications were used for the fatigue testing program.

1. The tests were conducted at a frequency $\boldsymbol{f}$ = 2Hz.
2. The infinite life $N_{\infty}$, was assumed to be 150,000 cycles.
3. The load ratios used were, $R_1$ =10, $R_2$ =5 and $R_3$ =2.
4. The specimens were inspected at intervals of 25000 cycles for damage growth.
    a. Compliance tests: The foam core and honeycomb core sandwich panels were statically loaded to about 40% of the minimum fatigue load level, the compliance associated with end-shortening and out-of-plane displacement at the impact location used as a measure of damage growth.
    b. TTU C-Scan: The honeycomb cores were inspected for growth in planar damage size in addition to the compliance measurements.

The sandwich specimens were subjected to fatigue loading using the load ratios defined in the previous section. The number of cycles to failure, $N_f$, at each load level and load ratio combination was recorded. The specimens surviving $N_{\infty}$ (=150,000) cycles were subsequently tested to failure under static loading to assess any further degradation in residual strength. The following observations were made regarding the fatigue life of sandwich specimens at different load levels.

- ~~a.The fatigue life at higher load levels exhibited dependence on the load ratio. The fatigue life decreased when the load ratio was increased. It is speculated that at higher load ratios, the damaged core may experience a transverse tensile stress field, which could lead to core fracture.~~
- a. At the higher fatigue loads the early failures are attributed to impingement on the static strength distribution. The S/N curve is very flat and comparable to other composite structures. No significant trend could be observed with load ratio.

- b. The change in compliance associated with the end shortening was insignificant for load levels at which the specimens lasted 150,000 cycles. Since most specimens that did fail before $N_\infty$ , had $N_f < 75000$ cycles, the compliance test interval (25,000 cycles) was too large to obtain enough data points to draw meaningful conclusions regarding compliance changes. Selected tests may have to be repeated to monitor the compliance changes at smaller intervals.

- c. The TTU C-Scan inspection of honeycomb core sandwich panels did not indicate a significant increase in damage size ($2R_{damage}$). Additional destructive tests at shorter intervals may be necessary to observe the growth of core damage across the thickness of the specimen.

The specimens surviving the predefined infinite life of 150,000 cycles were further tested for degradation in residual strength. Except for foam core sandwich panels impacted at a large energy level where the residual strength degradation was 30%,~~The~~ the ~~degradation in residual strength due to~~ fatigue cycling ~~was observed to be between 10 to 30 % of their static residual strength.~~did not degrade the static residual strength. It should be noted that the fatigue cycling was at strain levels much higher than would be expected in service.

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